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...ENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REP...
Unclassified

1b. RESTRICTIVE MARKINGS

DTIC ELECTE MAY 29 1990 S D

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release; distribution is unlimited.

(2)

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

D

5. MONITORING ORGANIZATION REPORT NUMBER(S)
AFOSR.TR. 90-0557

6a. NAME OF PERFORMING ORGANIZATION
Universtiy of California at Berkeley

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION
AFOSR/NA

6c. ADDRESS (City, State, and ZIP Code)
Dept. of Mechanical Engineering
Berkeley, CA 94720

7b. ADDRESS (City, State, and ZIP Code)
Building 410, Bolling AFB DC
20332-6448

8a. NAME OF FUNDING / SPONSORING ORGANIZATION
AFOSR/NA

8b. OFFICE SYMBOL (If applicable)
NA

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
AF OSR 86-0067

8c. ADDRESS (City, State, and ZIP Code)
Building 410, Bolling AFB DC
20332-6448

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.
61102F	2308	A3	

11. TITLE (Include Security Classification)
(U) LASER SPECTROSCOPY OF PLASMAS

12. PERSONAL AUTHOR(S)
John W. Daily

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 1/86 TO 6/89	4/27/90	25

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Plasmas, Laser Spectroscopy, Temperature, Electric Field, Flames

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

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20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL
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(202) 767-4935

22c. OFFICE SYMBOL
AFOSR/NA

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

LASER SPECTROSCOPY OF PLASMAS

John W. Daily

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Distribution /		
Availability Codes		
Dist	Avail and / or Special	
A-1		

04/27/90

Final Report

AFOSR Grant 86-0067

Center for Combustion Research
University of Colorado at Boulder
Boulder, CO 80309-0427

Table of Contents

1 Abstract 1

2 Introduction 1

3 The Diagnostic Method 2

4 LIF Diagnostics 5

5 Plasma Test Environment 5
5.1 Diffusionless Plasma Theory 6
5.1.1 Current-Voltage Characteristics 7
5.1.2 Spatial Ion Distributions 7
5.2 Effects of Diffusion 8

6 Temperature Diagnostics 9

7 Experimental Considerations 9
7.1 Laser Selection 9
7.2 Optical Arrangments 10
7.3 Flame Assisted Plasma 10

8 Experimental Results 10
8.1 Plasma Current-Voltage Characteristics 10
8.2 Spacial Profiles of the Plasma Properties 11

9 Status of the Diagnostic 11

10 Publications 12

11 Personnel 14

1 Abstract

A study has been conducted to develop novel advanced laser spectroscopy plasma diagnostic methods. The methods are based on observing the Doppler shift in the absorption lines of ionic species. The two methods studied are Velocity Modulated Laser Spectroscopy and Two-Beam Doppler Shift Laser Spectroscopy. The scientific goal of the work was to increase understanding of plasmas by making insitu measurements of ion drift velocities, concentrations and temperatures in a non-intrusive fashion. The scientific approach was to combine conventional laser spectroscopies with velocity detection. Using a method such as Rayleigh, fluorescence, or Raman scattering, one probes the Doppler profile of the species of interest, observing shifts in the Doppler profile that arise because of the presence of an electric field. The shift may be related to the ion mobility, and thus conductivity, if the electric field is known, or to the electric field if the mobility is known. Temperature and concentration may be recovered by the conventional means.

2 Introduction

The purpose of the work was to develop advanced laser spectroscopy methods to diagnose partially ionized plasmas. We focused on methods that are based on observing the Doppler shift in ionic spectra due to the presence of an ion drift velocity. Two particular methods we worked with were Velocity Modulated Laser Spectroscopy (VMLS) and Two Beam Doppler Shift Laser Spectroscopy (TBDSLS).

The scientific goal of the work was to increase understanding of the role of flow non-uniformities and plasma/wall interactions in plasma devices by making insitu measurements of electric field strength, ion mobilities, concentrations and temperatures in a non-intrusive fashion that allows point, one, and two-dimensional imaging.

The scientific approach is to use conventional laser spectroscopic methods such as Rayleigh scattering, Raman scattering, or fluorescence, to probe ion absorption line profiles. If there is an electric field present, the ions will experience a net force and undergo drift resulting in a shift in the position of the line profile. If the ion mobility is known, then the electric field component along the probe direction can be calculated. If the electric field driving the plasma is modulated, one will observe an oscillating shift in the line profile that arises because of the oscillating force imposed on the ions. The shift may be related to the ion mobility, thus conductivity.

Temperature and concentration may be recovered by conventional laser spectroscopic means. The methods are species and state selective, allowing one to make measurements on more than one species and to study the effect of internal mode nonequilibrium.

The merit of the methods lies in their ability to provide simultaneous measurements of important parameters in plasmas. The methods are well suited to multi-dimensional imaging. One may use an array detector to image lines and planes in addition to the more conventional point configuration.

During the first year of the program, the theoretical basis of the method was developed and our experimental facility was modified for the purpose of demonstrating its effectiveness. During the second year the global characteristics of a flame assisted plasma was studied to establish a known measurement environment. During the final year laser diagnostic measurements were made in the plasma environment to determine its detailed structure.

The results of the analyses and experiments that we conducted establish the operational parameters of an instrument system. In the following the findings of the study are presented.

3 The Diagnostic Method

The basis of Doppler shift methods for studying plasma conditions is that ionic species will experience a drift velocity when exposed to an electric field. The velocity experienced is of the form

$$\vec{\upsilon} = \mu_i \vec{E}$$

where μ_i is the ion mobility. Since the observed frequency at which an atom or molecule absorbes is shifted according to the Doppler relation

$$d\nu = \left(\frac{\nu_o}{c}\right)\upsilon$$

where υ is the component of ion velocity along the line of sight, by measuring the shift in frequency of the ions absorption line one can obtain the drift velocity. By appropriate interpretation of the experimental results, one may then obtain information regarding the mobility and the electric field.

The configurations we studied are Velocity Modulated Laser Spectroscopy (VMLS) and Two-Beam Doppler Shift Laser Spectroscopy (TBDSLS).

The VMLS configuration is useful for studying AC plasmas and for measuring mobility under known plasma conditions. As illustrated in Figure 1, one brings a laser beam into the plasma in a direction parallel to the electric field and then collects scattered fluorescence at ninety degrees. By using laser induced fluorescence to detect the ion and using a laser that has a line width narrow with respect to the absorption line width, the LIF signal can be used to probe the line. That is, as the laser frequency is scanned past the line, the signal will trace out the line shape. If one assumes that the line is Doppler broadened, then the signal will be proportional to

$$Sig \propto \left(\frac{2\sqrt{\ln 2}}{\Delta\nu_D\sqrt{\pi}}\right)\exp-\left(\frac{2\sqrt{\ln 2}}{\Delta\nu_D}(\nu-\nu_o)\right)^2$$

where $\Delta\nu_D$ is the Doppler half width.

The effect of velocity modulation on the Doppler profile is felt as a modulation of ν_o. By differentiating the signal twice, one obtains the result that the signal is most sensitive to changes in ν_o when the laser frequency ν_l becomes equal to $\nu_l = \nu_o \pm 0.425\Delta\nu_D$. The fractional sensitivity in this case is

$$\frac{dSig}{Sig} = 2.35\frac{d\nu_o}{\Delta\nu_D}$$

One may recast this expression into a detectabilty limit for the detection of a given modulation electric field

$$E_{o_{Det}} = 1.08\left(\frac{Q}{q}\right)P\left(\frac{dSig}{Sig}\right)_{Det}$$

If one assumes a moderate one percent for the signal detectability limit, and a typical ten square Angstroms for the collision cross section, then one obtains

$$E_{o_{Det}}(V/m) = 0.00675P(Pa)$$

At one atmosphere, the detectable electric field is only 6.75 V/cm, a field readily achievable in the laboratory. By utilizing phase sensitive detection, one can achieve significantly lower detectability limits.

In principle, any method which probes the Doppler profile with sufficient resolution can be used to determine a DC line shift. If only one probe is used, however, there may be a problem of absolute frequency calibration. By using two beams in opposite directions, an insitu calibration is achieved.

Consider the arrangement illustrated in Figure 2. Assume that there is a drift velocity in the positive x direction. If the laser frequency is scanned through the line, then the rightward running beam will probe the profile labeled R in the lower figure, while the leftward running wave will probe the profile labeled L.

As the laser frequency is scanned through the line (or lines as it were) from $\nu < \nu_0$ to $\nu > \nu_0$, signal will first appear from the right running beam. As the frequency is increased, the leftward running beam will begin to contribute. If the two signals are independently observed, they will look as shown in Figure 2. By chopping the beams at a rate fast compared to the frequency scan rate, one may use the same imaging optics to detect both signals. The peak separation is just twice the Doppler shift and the crossing point of the two signals is the unshifted line center.

The detectability limit for the method is determined by the resolution with which the distance between the two peaks can be resolved. If the precision with which the line shape signal can be measured is ΔSig, then for Doppler broadening the precision with which the separation in peaks, and thus electric field, can be resolved is

$$\frac{\Delta E}{E} = \left(1/\sqrt{2\ln 2}\right)\left(\frac{\Delta\nu_D}{\Delta\nu_E}\right)\left(\frac{\Delta Sig}{Sig}\right)^{\frac{1}{2}}$$

where $\Delta\nu_E$ is the frequency shift due to the electric field.

If we define the detectability limit as that value of E for which a precision of 10% is achieved when the spectroscopic signal is detected with a precision of 1%, then we can write approximately

$$E_{det}(V/cm) \approx 0.04\frac{P(At)}{T(K)^{1/2}}$$

(Assuming that Q = 10 A^2, m is the mass of a proton, and the line center is at 5000 A.) Thus at a pressure of 0.01 Atmosphere and 5000K, the detectability limit is about 1 V/cm.

It should be noted that least squares fitting the line shape to the appropriate profile would significantly increase the precision with which the line center is detected and thus reduce the detectability limit for the electric field. Also, if a suitable transition is found, saturation spectroscopy could be used to locate the line peak with high precision, although the in situ calibration for the zero shift position would be lost.

4 LIF Diagnostics

One must select a diagnostic to measure the line profile shape and position. Because of signal considerations, LIF is the method of first choice. Of importance are the excitation dynamics relating to the pumping and probe strategy, and the nature of the detection system.

The excitation dynamics are important because they play a critical role in determining the detectablity limit with which the line shape profile can be obtained. This is a serious problem in application because the ion populations drop significantly in regions of high electric fields and because we are pumping at sub-Doppler widths and thus not exciting all the ground state population. One seeks to maximize LIF signal at all times.

We have worked with the Barium ion. A simple energy level diagram is shown in Figure 3. Because of the difficulty in operating the ring laser in the blue, we have chosen to excite from the $^2D_{3/2}$ metastable state to the $^2P_{3/2}$ excited electronic state at a wavelength of 5853.68 A. We then detected fluorescence to the $^2S_{1/2}$ ground state at 4554.03 A.

The excitation dynamics were modeled using a lumped two-level system as illustrated in Figure 4. Solving the steady state rate equations results in

$$n_T = \left\{ \frac{\alpha \beta W_{25}}{A_{51} + Q_{\bullet 0} + W_{25}\left(\alpha + \frac{g_2}{g_1}\beta\right)} \right\} n_5$$

where n_5 is the directly measured population of level 5. Thus the propceedure is based on measuring the population of level 5 under laser excitation conditions.

5 Plasma Test Environment

The selection of a plasma environment in which to demonstrate the Doppler shift methods is somewhat complicated by the fact that the plasmas of ultimate interest are quite complex and not well understood. Thus the approach we took was to select a plasma environment which may be fairly well characterized and which displays simple limiting behavior.

After some consideration, it was decided to work with a flame assisted plasma. The concept behind such a choice is that flame assisted plasmas that are seeded with a dominant ionizable species often remain collision dominated at quite large values of electric field, and may be designed to offer well defined properties over fairly large spacial extent.

Once a seeded, flame assisted plasma is selected, other practical constraints limit the choices of configuration, fuel and seed species. The seed species must be both readily ionizable and the ion's absorption lines must be accessible for laser excitation. In addition, one seeks to achieve as high a temperature as possible so as to obtain the maximum degree of ionization. Given these constraints, barium was chosen as the seed species and oxygen and hydrogen as the oxidizer and fuel, respectively. The use of oxygen and hydrogen limits the choice of a burner configuration to non-premixed.

5.1 Diffusionless Plasma Theory

The advantage of utilizing a collisionally dominated plasma is that the theoretical description of the plasma is simplified considerably. Such a simplified description has been formulated by Lawton and Weinberg [1] expressly for flames under conditions where the flow between electrodes is fully developed or quiescent. Our approach has been to use their theory in conjunction with experiments to ensure that we have a reasonable understanding of the plasma conditions.

The Lawton and Weinberg theory is based on the assumption that diffusion of ions and electrons can be neglected in comparison with drift. Under this assumption, and assuming that the plasma is one-dimensional with uniform properties, the governing equations are electron and ion continuity

$$\frac{dJ_{\pm}}{dx} = r_i$$

and Poisson's equation

$$\frac{dE}{dx} = \frac{e}{\epsilon}(n_{+} - n_{-})$$

$J_{\pm}$ is the ion or electron current density in units of molecules per unit area and time, r_i the net rate of charge production in units of molecules per unit volume and time, E the electric field, e the charge of an electron, ϵ the permutivity of free space, and $n_{\pm}$ the ion or electron number density. The current density is given by

$$J_{\pm} = \pm\mu_{\pm} n_{\pm} E$$

where $\mu_{\pm}$ is the ion or electron mobility, and the electric field is related to the potential by

$$\frac{dV}{dx} = -E$$

5.1.1 Current-Voltage Characteristics

These equations have particularly simple limiting solutions. The first is the zero-field limit. In this case it is assumed that the electric field is sufficiently small so that the imposed ion and electron currents are insignificant in comparison to the ionization rate. In this limit, the ion and electron number densities remain at approximately their equilibrium values and the source term in Poisson's equation remains zero. Thus the electric field is constant and given by

$$E = \frac{V_0}{L}$$

where V_0 is the potential across the electrodes, and L is the electrode spacing.

The other simple limit occurs at large field strengths and is called the saturation limit. If the field becomes large enough, then the current is limited by the ionization rate. In this limit the current becomes

$$J_{sat} = e r_c L$$

where r_c is the collisional ionization rate. The electric field is given by

$$E = 2\frac{V}{L}\left(\frac{V}{L}\right)$$

In between these two limiting solutions, the current density depends on the square root of the voltage drop across the plasma

$$\frac{J}{J_{sat}} = \sqrt{\frac{V}{V_{sat}}}$$

If the theory is correct, then the drift velocity of ion we are observing in the experiment can be calculated directly. This gives a basis of comparison with the Doppler shift measurements. Furthermore, the theory allows one to determine the ionization rate and the equilibrium ion number density from the current-voltage characteristics of the plasma.

5.1.2 Spatial Ion Distributions

The field equations can also be solved for the electron and ion distributions in the limiting cases discussed above. For the zero-field limit, the electron and ion number densities are given by their thermal equilibrium values (note that in flames there may be a high degree of ionizational non-equilibrium.) In the saturation limit, the electron number density is reduced

practically to zero and the positive ion number density to a value determined by the balance between current and ion production

$$n_{+} = \left(\frac{\epsilon r_c}{e \mu_{+}} \right)^{\frac{1}{2}}$$

In practice this means that the ion number density may be reduced by several orders of magnitude below the zero field value. For sub-saturation conditions, there exists an expanded sheath region, within which the electron number density is essentially zero and the positive ion number density reduced to the saturation value. The above results are shown in Figures 5-7.

5.2 Effects of Diffusion

Diffusion is important in practice because of the tendancy for recombination to occur on cold electrode surfaces. In addition, if the flow field between the electrodes is not fully developed, diffusion will play a role in determining the electron and ion profiles.

If diffusion is included in the theory, the drift velocity becomes

$$v_{\pm} = \pm \mu_{\pm} E \pm D_{\pm} \frac{d \ln n_{\pm}}{dx}$$

In the case of zero field, one would expect approximately a parabolic profile for both electrons and ions. This is because the continuity equation reduces to

$$-D \frac{d^2 n}{dx^2} = r_i$$

where n is the electron or ion number density and r_i is the net rate of charge generation. If the boundary conditions on the electrodes assume complete recombination, then

$$n(x) = \frac{r_i}{D} \; x_0^2 - x^2$$

where x_0 is the electrode spacing. Thermal diffusion will also lead to a parabolic temperature distribution. This in turn will affect the neutral barium concentration distribution and the net charge production. Thus the above result should be modified to account for these effects.

In the presence of a field, the qualitative results of the diffusionless theory would still apply. There will be a sheath region that grows from zero (of neglegible) thickness at zero field, to the full plasma width at saturation. Within the sheath, the electron concentration is effectively zero and the ion concentration determined by the balance between production and current.

6 Temperature Diagnostics

A program was written to fit temperature to single spectral line data. The program fits the line shape to a Voigt profile of the form

$$S(\xi) = S_0 \phi(\xi, a)$$

where $\phi(\xi, a)$ is the Voigt function

$$\phi(\xi, a) = \frac{a}{\pi} \int_{-\infty}^{+\infty} \exp \frac{-y^2}{a^2 + (\xi - y)^2} dy$$

ξ is the normalized frequency

$$\xi = \frac{2\sqrt{\ln 2}\,|\nu - \nu_0|}{\Delta \nu_D}$$

and a is the Voigt parameter

$$a = \frac{\Delta \nu_c}{\Delta \nu_D} \ln 2$$

The fit procedure is based on minimizing the sum of the squares of the non-normalized residual error between $S(\xi)$ and the experimental line profile over all the data points.

7 Experimental Considerations

7.1 Laser Selection

To perform a measurement one must utilize a laser source of sufficiently small line width and sufficiently large power. The first requirement is to insure that the absorption line of the transition being probed can be fully resolved. The second is to insure adaquate signal. As will be discussed below, the latter issue can be significant.

There are two approaches that may be followed. The first is to utilize a CW laser system such as an optically pumped ring dye laser. The second is to use a pulsed system, such as amplifying the ring output with an excimer or YAG pumped dye cell.

In our experiments we utilized an argon ion laser (Spectra Physics 171-19) pumped ring dye laser (Coherent 699-21). The ring laser was fully stabilized and has a line width of less than one megahertz. The output of the laser was directed through a Fabry-Perot interferometer (Coherent Model 251 Spectrum Analyzer) as a means of measuring the relative wavelength precisely. A small portion of the beam was also split off and sent to a wavemeter (Burleigh Model WA 10) for absolute wavelength calibration.

7.2 Optical Arrangments

The laser beam was then directed into the test section in either the VMLS or TBDSLS configuration. In either case (see Figure 8), the beam (or beams) passes through small holes in the electrodes. A power supply capable of delevering several hundred volts DC modulated at up to 100 VAC was connected to the electrodes. The signal was detected by observing the fluorescence at ninety degrees. The signal was collected with F/9 optics and passed through a 1/2 meter Jarrell-Ash monochromator. A RCA 1P28 photomultiplier was used as the detector.

7.3 Flame Assisted Plasma

The flame assisted plasma is generated inside a low pressure vessel. The vessel is constructed from stainless steel and is mounted with windows and instrumentation ports. The burner we have chosen is a capillary, diffusion flame burner obtained from the University of Florida. The non-premixed burner allows a wide range of operating conditions without the normal difficulties associated with using hydrogen and oxygen as reactants, and can be operated down to about 20 Torr. Barium tetrachloride is seeded into the flame using a Perkin-Elmer aspirator modified to operate at lower pressures. Electrodes are mounted adjacent to the flame. A combination of a DC power supply and audio power amplifier/signal generator allows delivery of up to several hundred volts DC or AC.

8 Experimental Results

8.1 Plasma Current-Voltage Characteristics

Typical current-voltage results for several seeding levels are shown in Figure 9. The curve displays the square root dependency and the linear and saturation regimes. As the level of seeding is increased, the saturation current increases. Thus by varying the seeding rate, one can significantly change the domain of behavior.

8.2 Spacial Profiles of the Plasma Properties

Spacial profiles of the barium ion number density were obtained using LIF under a variety of conditions. Typical results are shown in Figure 10 for a DC field applied such that the sheath grows from left to right. As can be seen, the zero field ion profile is symmetric about the centerline and approximately parabolic. As the field is increased, the absolute value of concentration drops and the profile shifts to the right. The point where the concentration becomes undetectable on the left marks the approximate righthand boundary of the sheath.

Spacial profiles of the temperature are shown in Figure 11 for a case without electric field. (Because of systematic uncertainty in the absolute temperature, the data were scaled to the adiabatic flame temperature at the center of the plates.) As can be seen, the temperature profile is approximately parabolic in a fashion similar to the number density profiles.

9 Status of the Diagnostic

Our findings may be used to establish the operating constraints of the use of Doppler shift methods. The major result is that due to ion transport, ion densities drop by as much as three orders of magnitude in regions of large electric field. As a consequence, the diagnostic is limited by signal to noise, rather than Doppler shift resolution.

One may estimate the concentration levels that must be detectable for the LIF detection to operate. The detectability limit for the five level barium system may be expressed in terms of an acceptable singal to noise ratio as

$$n_{det} = C\left\{ \frac{A_{51} + Q_{e0} + W_{25}\left(\alpha + \frac{g_2}{g_1}\beta\right)}{\alpha\beta W_{25}} \right\}\left(\frac{S}{N}\right)^2$$

where C is a constant that takes into account all optical parameters and the expression in the brakets is the ratio of the level 5 population to the total population under excitation conditions. Under the conditions for which our data was taken, the signal to noise ratio of our results when no electric field was present was approximately 100:1 at the center of electrode plates. This gave adaquate results when no electric field was present. However, as the barium ion concentration in sheath dropped, the signal to noise ratio droped to the point where the signal could not be separated from the noise.

There are several steps that could be taken to reduce the detectability limit. The optical focal volume could be enlarged by as much as a factor of ten without serious compromise of spacial resolution. To take advantage of this enlargement more laser power, approximately a factor of two or three, would be required to maintain a condition of near saturation. The solid angle could be increased by a factor of five with larger F/# optics. Finally, the sampling time could be increased by a factor of 100 without too much difficulty. These changes, all possible with presently available equipment, would result in a three to four order of magnitude decrease in the detectability limit. Such a decrease would make measurments in the sheath possible and bring the diagnostic to the application in interesting experiments. With some attention to signal processing, further gains in detectability are possible.

10 Publications

a) AFOSR sponsored publications appearing, accepted, or in progress:

Daily, J. W., "Electric Field Measurement by Two-Beam Doppler Shift Spectroscopy," Applied Optics, Vol. 25, 1378-1380 (1986).

M. Sassi, and J. W. Daily, "Doppler Shift Methods for Plasma Diagnostics," AIAA 22nd Thermophysics Conference, Honolulu, Hawaii, Paper 87-1528 (8-10 June 1987).

M. Sassi, and J. W. Daily, "Doppler Shift Methods for Plasma Diagnostics," Journal of Quantitative Spectroscopy and Radiative Transfer, Vol. 40, 429-437 (1988).

Daily, J. W., "Laser Induced Fluorescence Spectroscopy in Flames," Invited review for Progress in Energy and Combustion Science, In progress.

Sassi, M., J. Hwang, and J. W. Daily, "Characterization of a Flame Assisted Plasma for Validation of Laser Based Doppler Shift Spectroscopy," In progress.

Sassi, M., J. Hwang, and J. W. Daily, "Laser Spectroscopy of a Flame Assisted Plasma," In progress.

Sassi, M. and J. W. Daily "Single Spectral Line Fit for Temperature Measurement," In progress.

c) Reports

Lee, C., "Current-Voltage Characteristics of a Flame Assisted Plasma for Plasma Diagnostics," University of California, Master Degree Project Report (1987)

"Laser Spectroscopy of Plasmas," Annual Technical Report to AFOSR 12/85-12/86 (15 May 1987)

"Laser Spectroscopy of Plasmas," Annual Technical Report to AFOSR 12/86-12/87 (10 February 1988)

Sassi, M., "Laser Spectroscopy of a Flame Assisted Plasma," Ph.D. Dissertation, Department of Mechanical Engineering, University of California at Berkeley, Berkeley, California (1990)

d) Meetings

"Plasma Studies Using Doppler Shift Laser Spectroscopy," AFOSR Contractors Meeting, Stanford University (16-17 June 1986)

"Electric Field Diagnostics Using Doppler Shift Spectroscopy," Conference on Quantitative Spectroscopy and Laser Diagnostics, University of California, San Diego, La Jolla, CA (7-8 July 1986)

"Measurement of CH Radical Concentrations in an Acetylene/Oxygen Flame and Comparisons to Modeling Calculations," (With R. G. Joklik and W. J. Pitz) 21st International Symposium on Combustion, Munich, West Germany (3-8 August 1986)

"Plasma Diagnostics for Arcjet Plume Studies," Arcjet Plume Diagnostics Technical Workshop, Jet Propulsion Laboratory, Pasadena, California (2-3 October 1986)

"Doppler Shift Methods for Electric Field and Mobility Measurement in Plasmas," Invited paper, OSA Annual Meeting, Seattle, WA (21-25 October 1986)

"Doppler Shift Methods for Plasma Diagnostics," AIAA 22nd Thermophysics Conference, Honolulu, Hawaii, Paper 87-1528 (8-10 June 1987).

"Laser Diagnostics in Plasmas," Gordon Conference on Chemistry and Physics of Laser Diagnostics in Combustion, Plymouth, New Hampshire (13-17 July 1987)

"Doppler Shift Methods for Studying Ion Transport in Plasmas," Spring Meeting of the Materials Research Society, Reno, Nevada (5-9 April 1988).

"Laser Spectroscopy of Plasmas," AFOSR Contractors Meeting, Monrovia, California (13-17 June 1988)

"Characterization of a Flame Assisted Plasma for Validation of Laser Based Doppler Shift Spectroscopy," 22nd Symposium (International) on Combustion, Seattle, Washington (14-19 August 1988)

"An Overview of Advanced Diagnostic Methods for Scramjet Development," POCM Exhaust Diagnostics Workshop, Joint Project Office/NASP, Arnold Engineering and Development Center, Tullahoma, Tennessee (23-24 August 1988)

"Laser Spectroscopy of a Flame Assisted Plasma," 1990 Spring Technical Meeting, The Combustion Intitute/Canadian and Western States Sections, Bannf, Alberta, 28 April-2 May (1990)

"Laser Spectroscopy of a Flame Assisted Plasma," 23rd Symposium (International) on Combustion, Orleans, France, 22-27 July (1990)

e) Seminars

"Combustion Diagnostics at Berkeley," Industrial Liason Program, UC Berkeley, CA (12 March 1986)

"Doppler Shift Methods for Measuring Drift Velocities in Plasmas," National Bureau of Standards, Gaithersburg, MD (5 May 1988)

11 Personnel

The principle investigator has been Professor John W. Daily. Professor Daily is currently a Professor of Mechanical Engineering and Director of the Center for Combustion Research at the University of Colorado at Boulder. During the grant period he was an Associate Professor (with tenure) of Mechanical Engineering at the University of California at Berkeley.

Four graduate students have worked on the project. These are Mohamed Sassi, who has completed his Ph.D., Jungho Hwang, a Ph.D. student who contributed to the project, and Paymon Aliabadi and Carolyn Lee, Masters Degree students, who finished their degrees in June of 1986 and December of 1987 respectively.

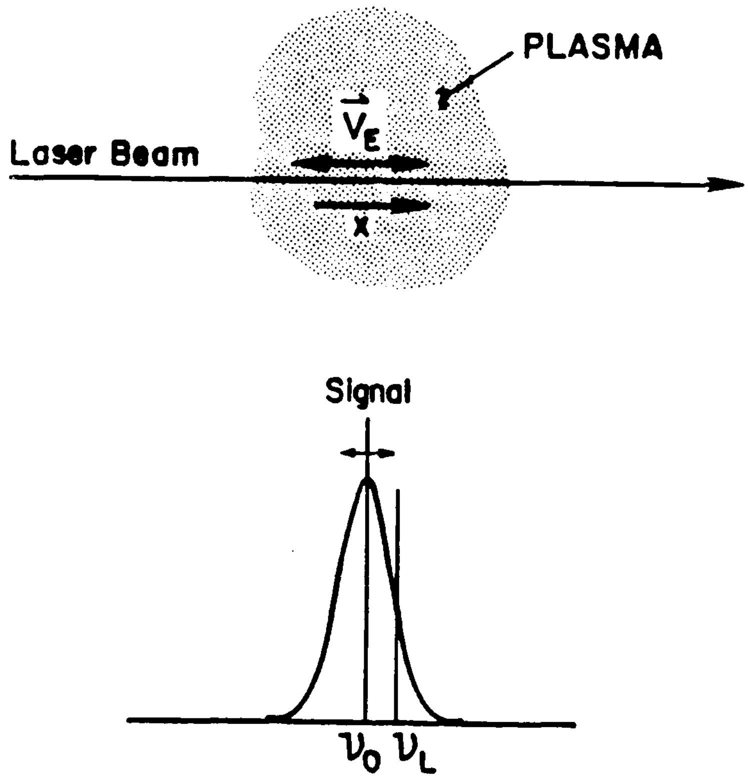

Figure 1. Velocity modulated laser spectroscopy

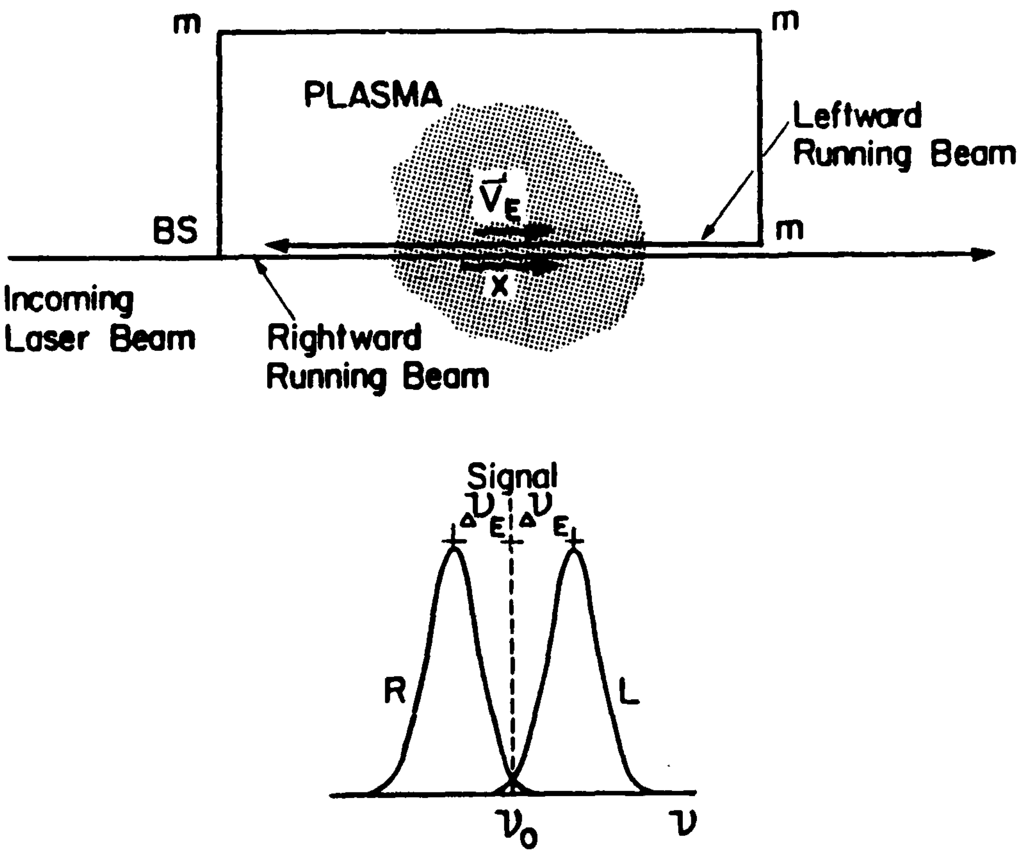

Figure 2. Two-beam Doppler shift laser spectroscopy configuration

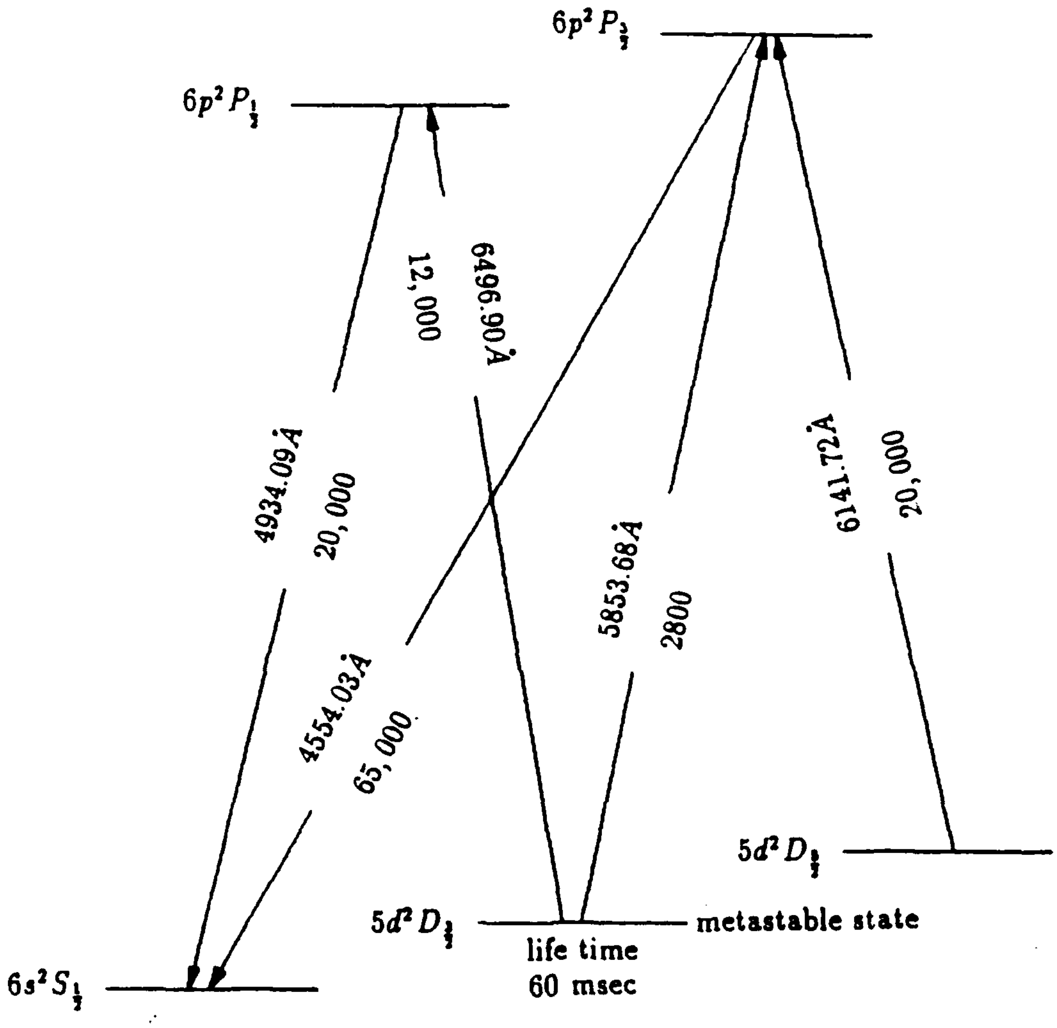

Figure 3. Barium ion energy-level diagram

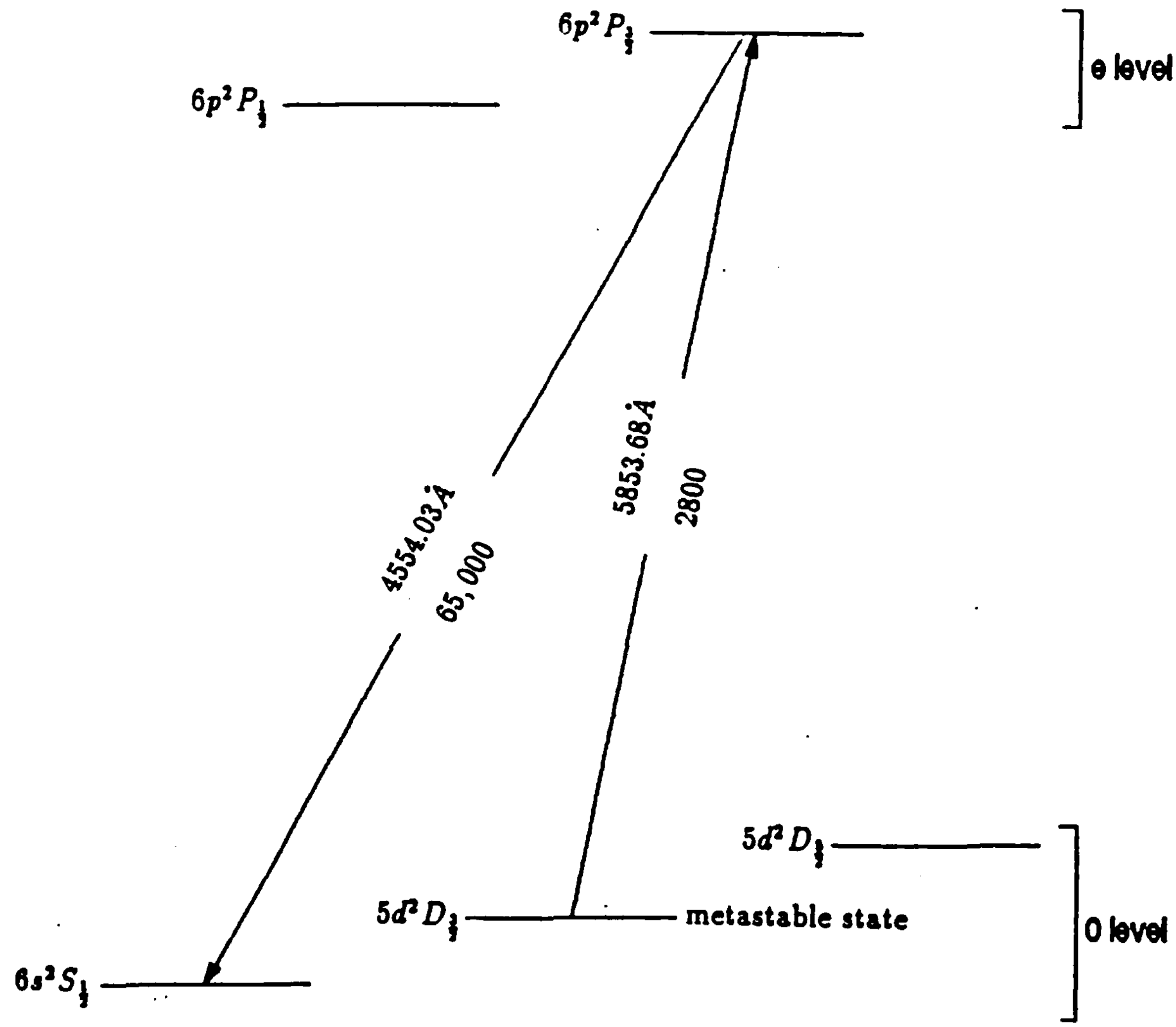

Figure 4. The lumped two-level system for the barium ion energy diagram

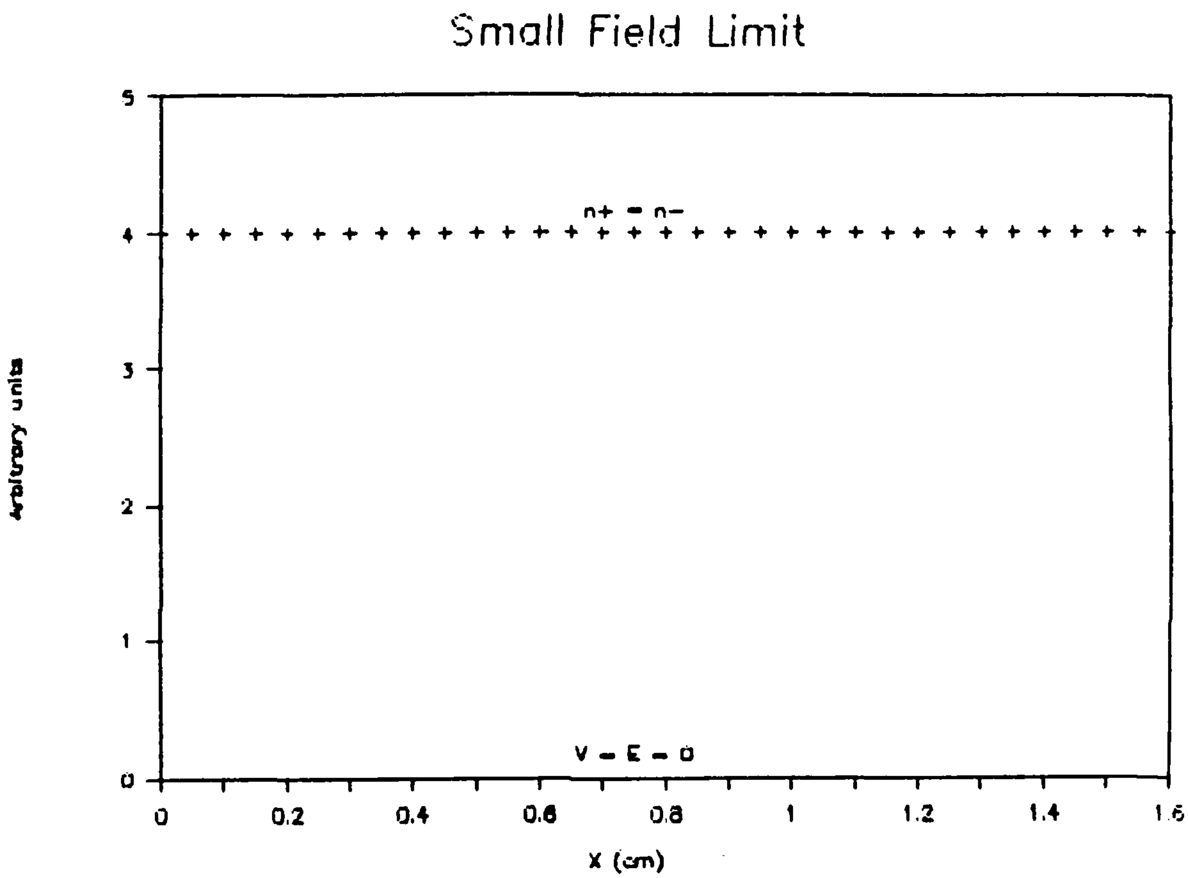

Figure 5. Electric field, voltage, and number density distributions for the small field limit

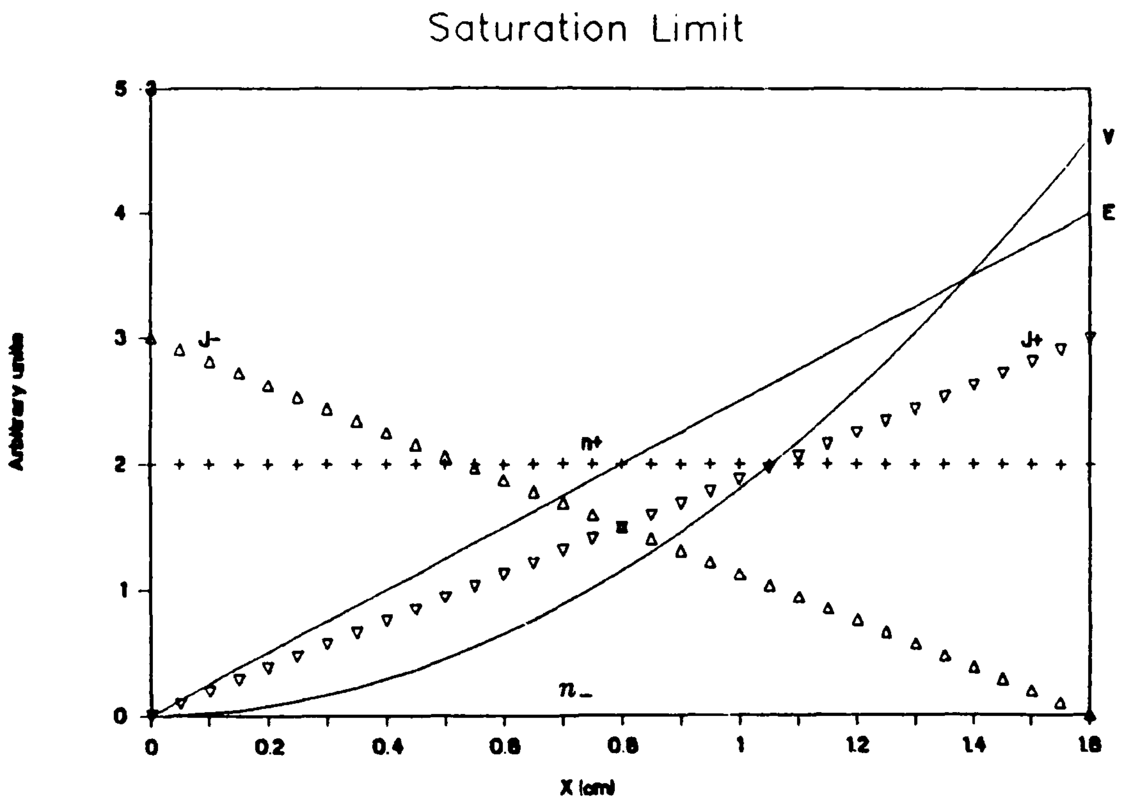

Figure 6. Electric field, voltage, current density, and number density density distributions for the saturation limit

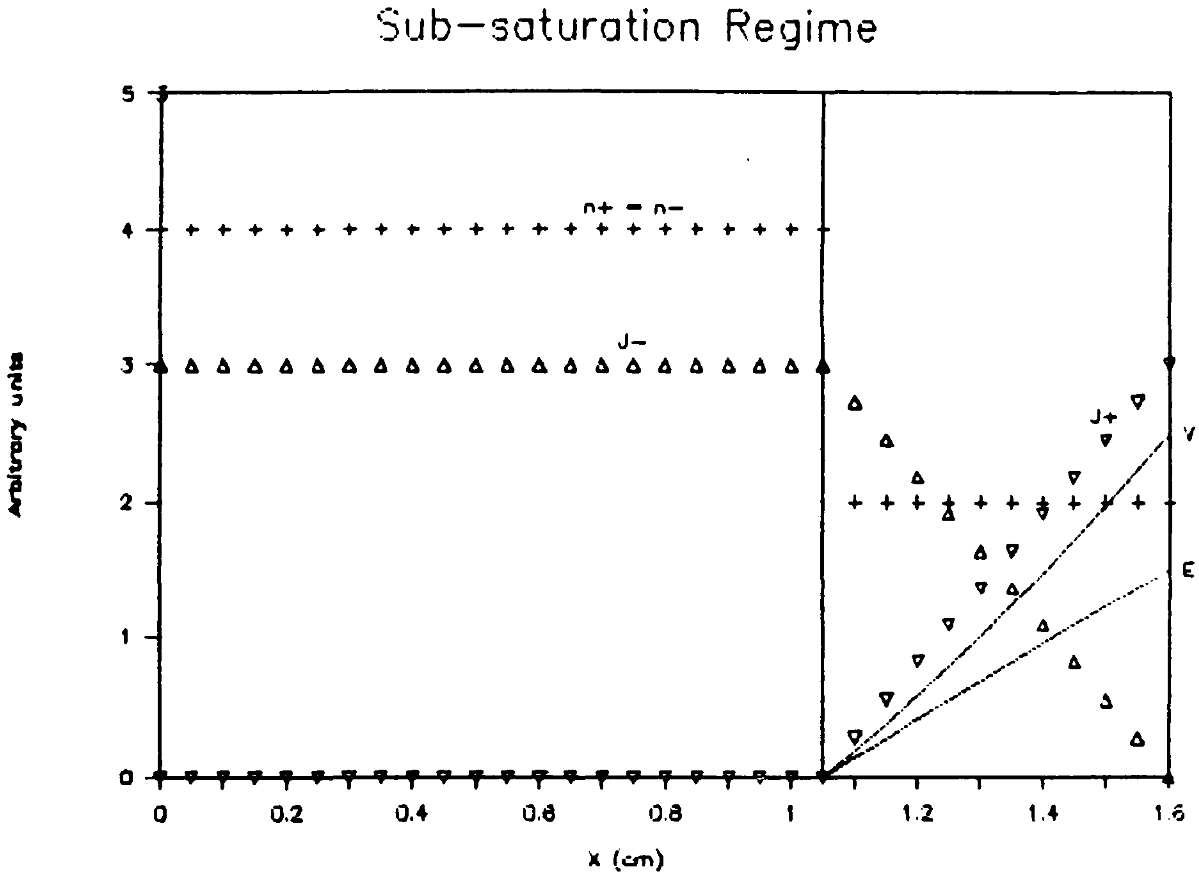

Figure 7. Electric field, voltage, current density, and number density distributions for the subsaturation regime

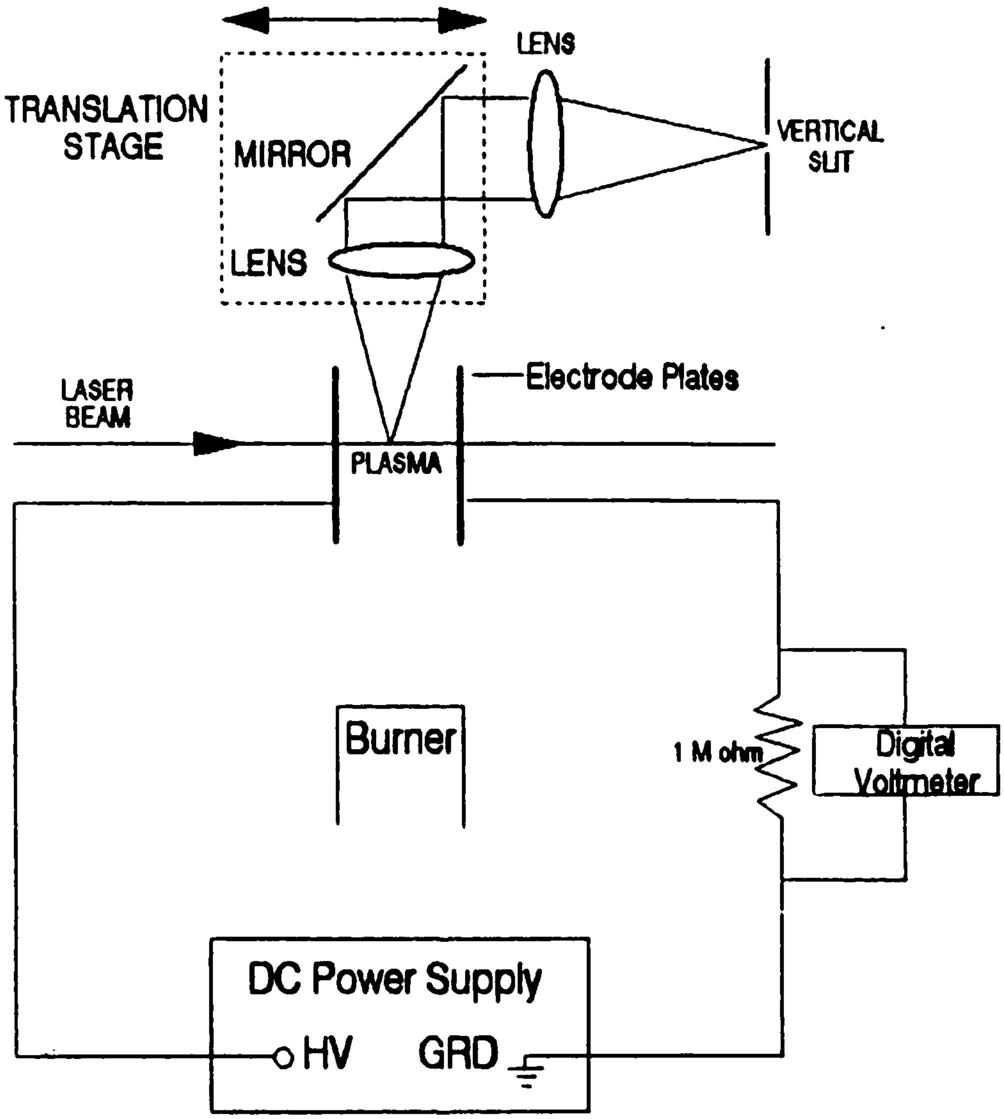

Figure 8. Vertical slit collection optics that allow horizontal translation of the collection volume

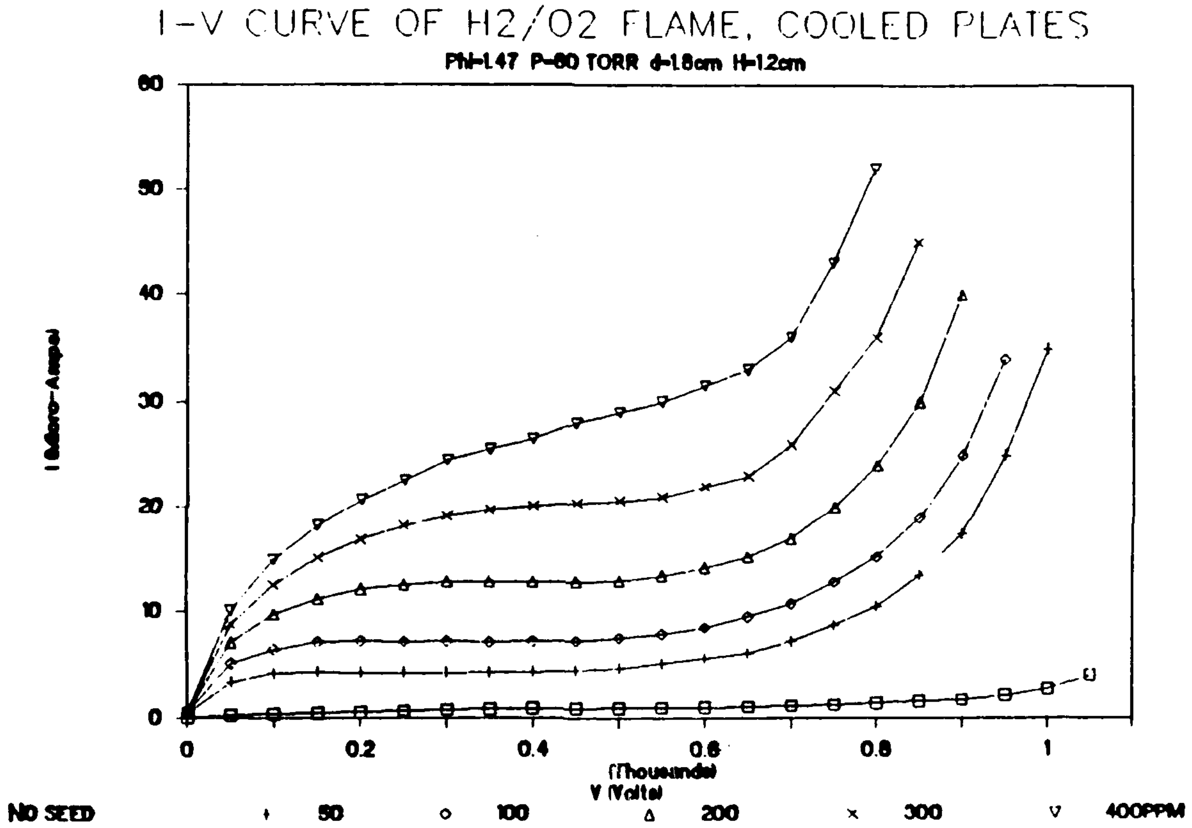

Figure 9. I/V characteristic curves of the H_2/O_2 flame with water cooled electrodes

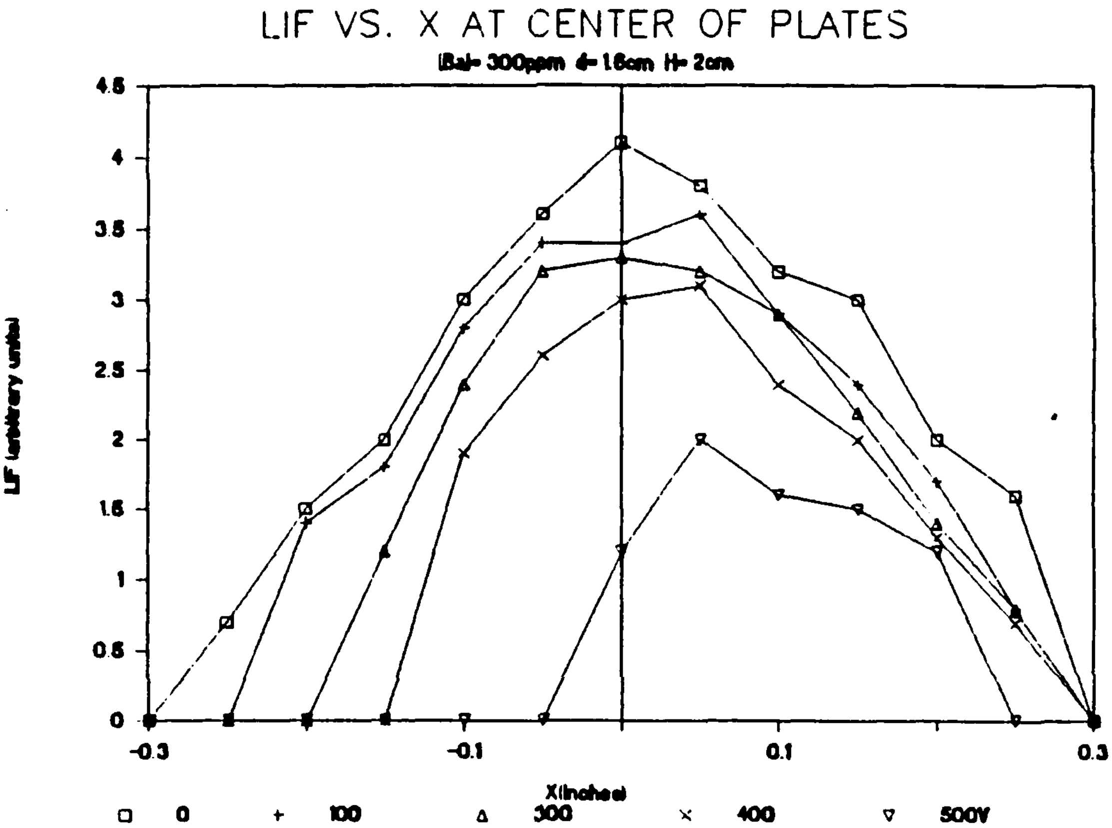

Figure 10. The relative barium ion LIF signal as a function of axial position between the plates, for [Ba]= 300ppm, and at different applied voltages. The laser crossed the plasma at the center of the plates. The flame was H_2/O_2 at $\phi = 1.4$, p=65 torres, d=1.6 cm, and H=2 cm. The left electrode (x= -0.3) was powered.

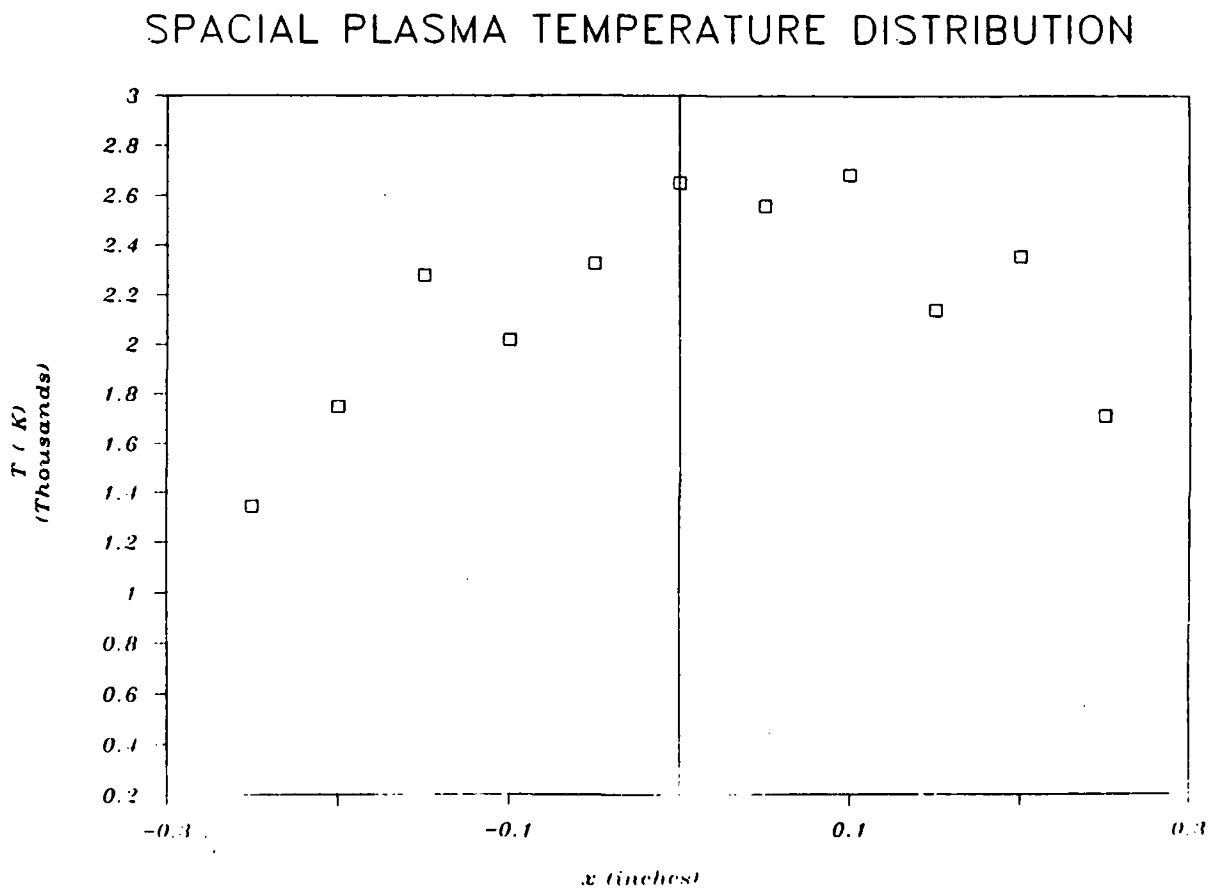

Figure 11. The spatial temperature distribution in the plasma recovered by the single spectral line fit. The flame conditions are those of the last figure.